Millennial-scale Vulnerability of the Antarctic Ice Sheet to localized subshelf warm-water forcing

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Joint work with:

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- Tony Payne (Bristol)
- Vicky Lee (Bristol)
- Esmond Ng (LBNL)
- Stephen Price (LANL)

Motivation: Potential future Sea Level Rise

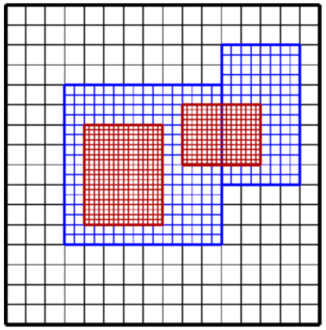
- Potentially large Antarctic contributions to SLR resulting from marine ice sheet instability, particularly from WAIS.
- Climate driver: subshelf melting driven by warm(ing) ocean water intruding into subshelf cavities.
- Evidence that this is already underway in ASE sector. (possibly Totten too?)
- Paleorecord implies that WAIS has deglaciated in the past.

Questions we'd like to answer:

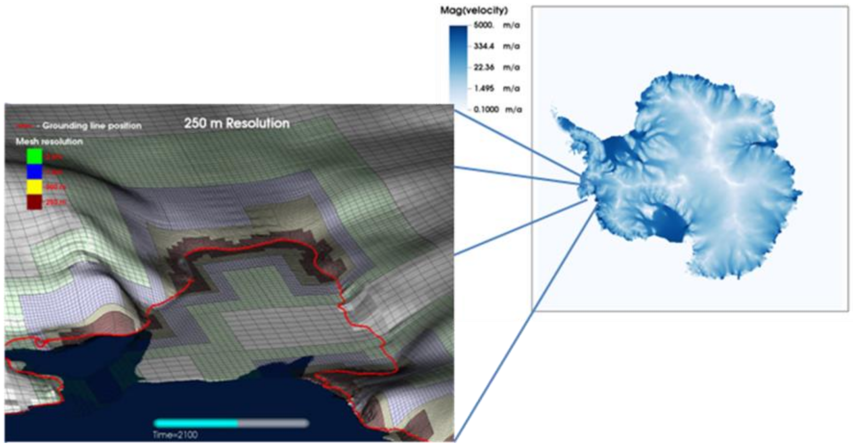
- **Credibility of simulations:**
  - Mesh-resolution requirements for "realistic" Antarctic MISI (vs. MISMIP3D)
- **Assess vulnerabilities:**
  - Where is the Antarctic Ice Sheet vulnerable to instability driven by warm-water incursion into subshelf cavities?

BISICLES Ice Sheet Model

- Scalable adaptive mesh refinement (AMR) ice sheet model
  - Dynamic local refinement of mesh to improve accuracy
- Chombo AMR framework for block-structured AMR
  - Support for AMR discretizations
  - Scalable solvers
  - Developed at LBNL
  - DOE ASCR supported (FASTMath)



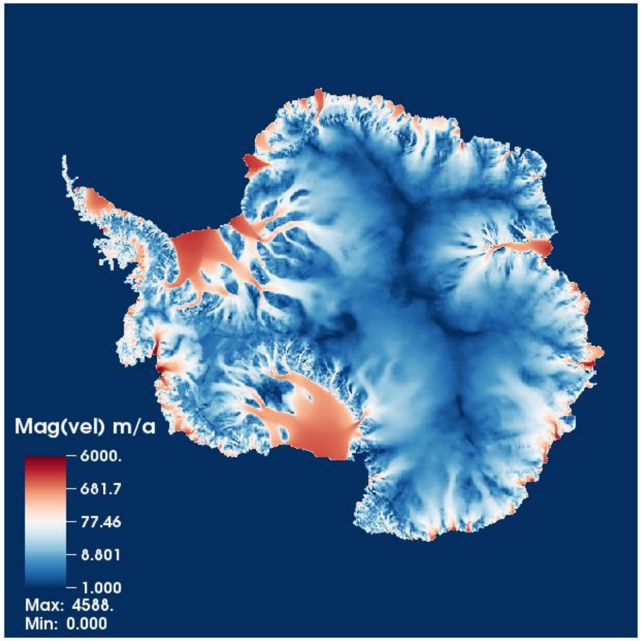
- Collaboration with Bristol (U.K.) and LANL
- Variant of “L1L2” model (Schoof and Hindmarsh, 2009)
- Coupled to Community Ice Sheet Model (CISM).
- Users in Berkeley, Bristol, Beijing, Brussels, and Berlin…

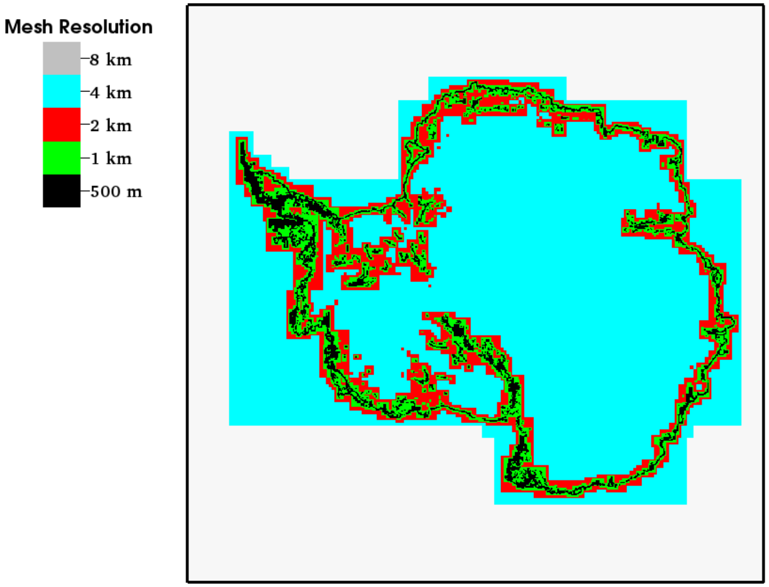


Mesh resolution requirements for marine AIS

Initial Condition for Antarctic Simulations

- Full-continent Bedmap2 (2013) geometry
- Temperature field from Pattyn (2010)
- Initialize basal friction to match Rignot (2011) velocities
- SMB: Arthern et al (2006)
- AMR meshes: 8 km base mesh, adaptively refine to Δx_f

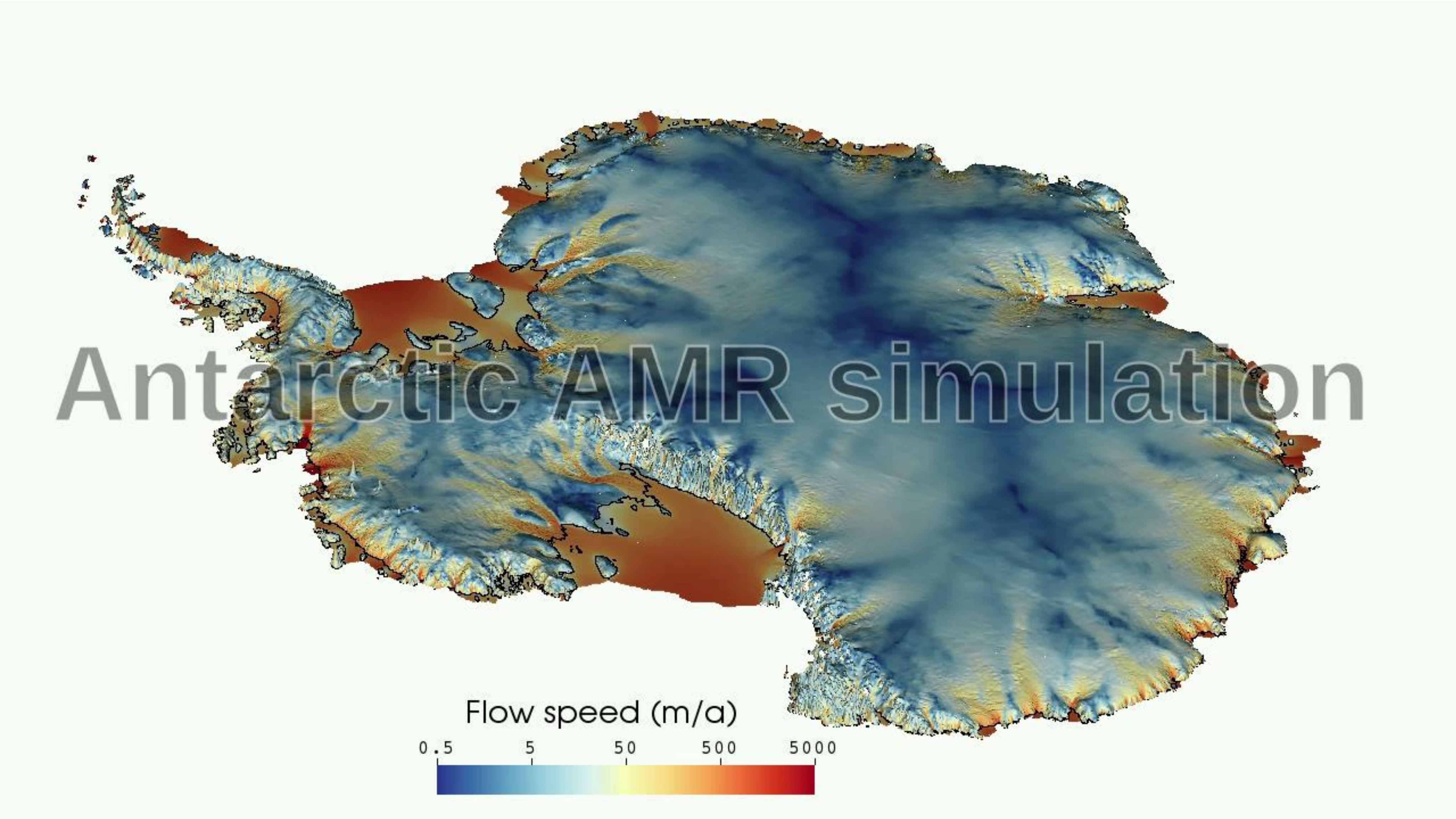




Experiment – 1000-year Antarctic simulations

- Range of finest resolution from 8 km (no refinement) to 500m (4 levels of factor-2 refinement)
- Subgrid basal friction parameterization (e.g. Seroussi et al)
  - Experience shows that it buys us about a factor of 2x
- At initial time, subject ice shelves to extreme (outlandish) depth-dependent melting:
  - No melt for h < 100m
  - Range up to 800m/a where h > 400m.
  - **No melt applied in partially-grounded cells**
- For each resolution, evolve for 1000 years

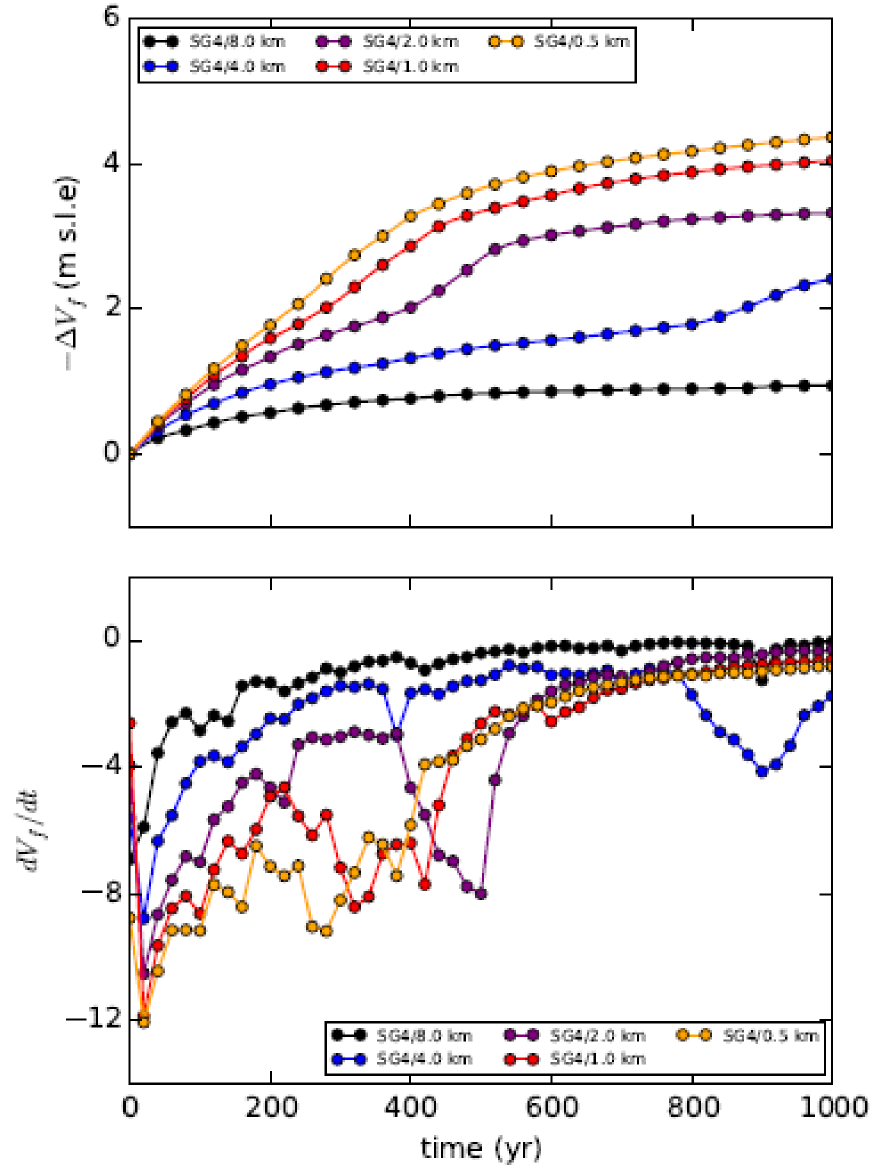
Results:



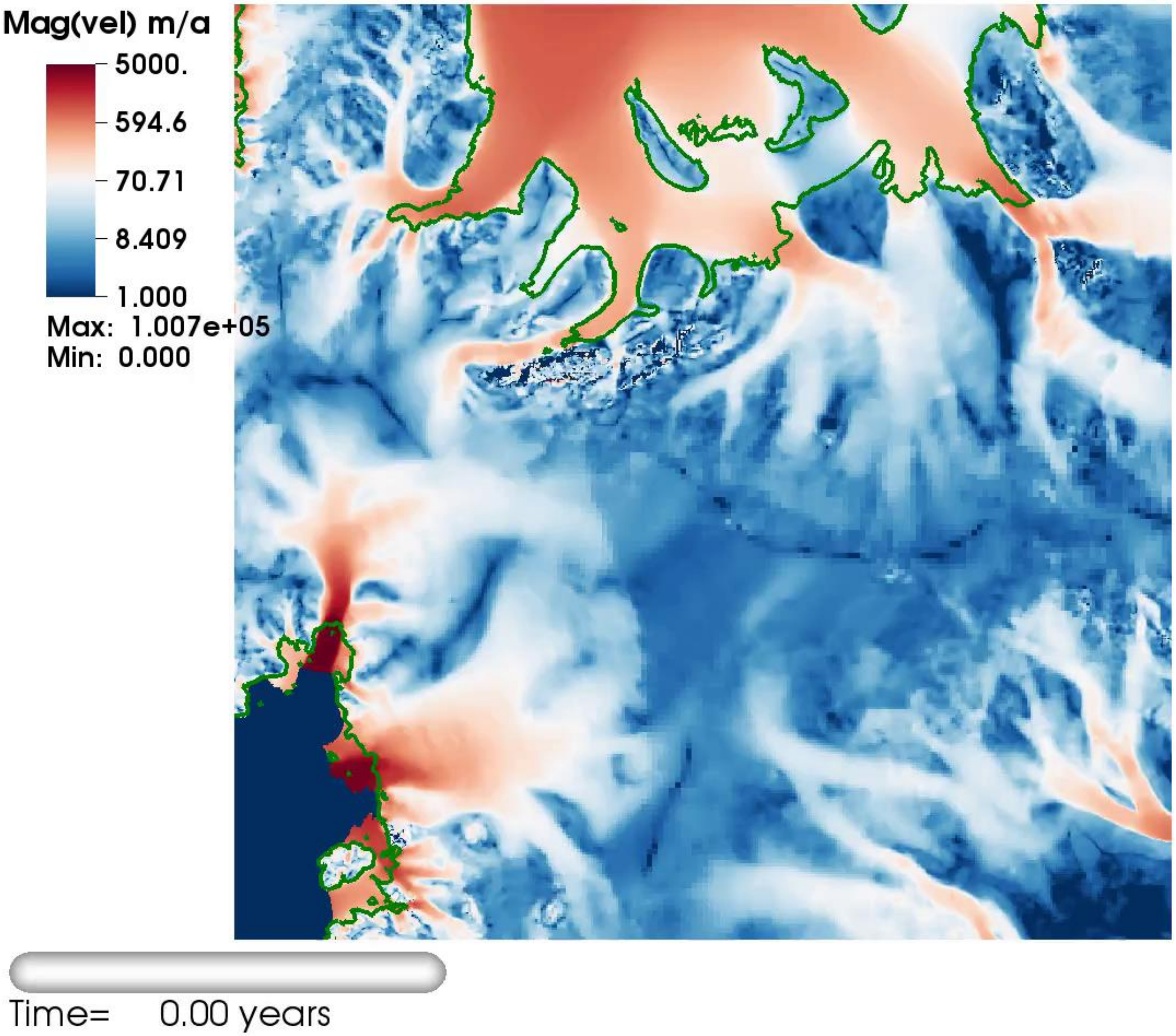
Results, cont.

- **Upper plot** – Change in VoF
  - Convergent at sufficient resolution

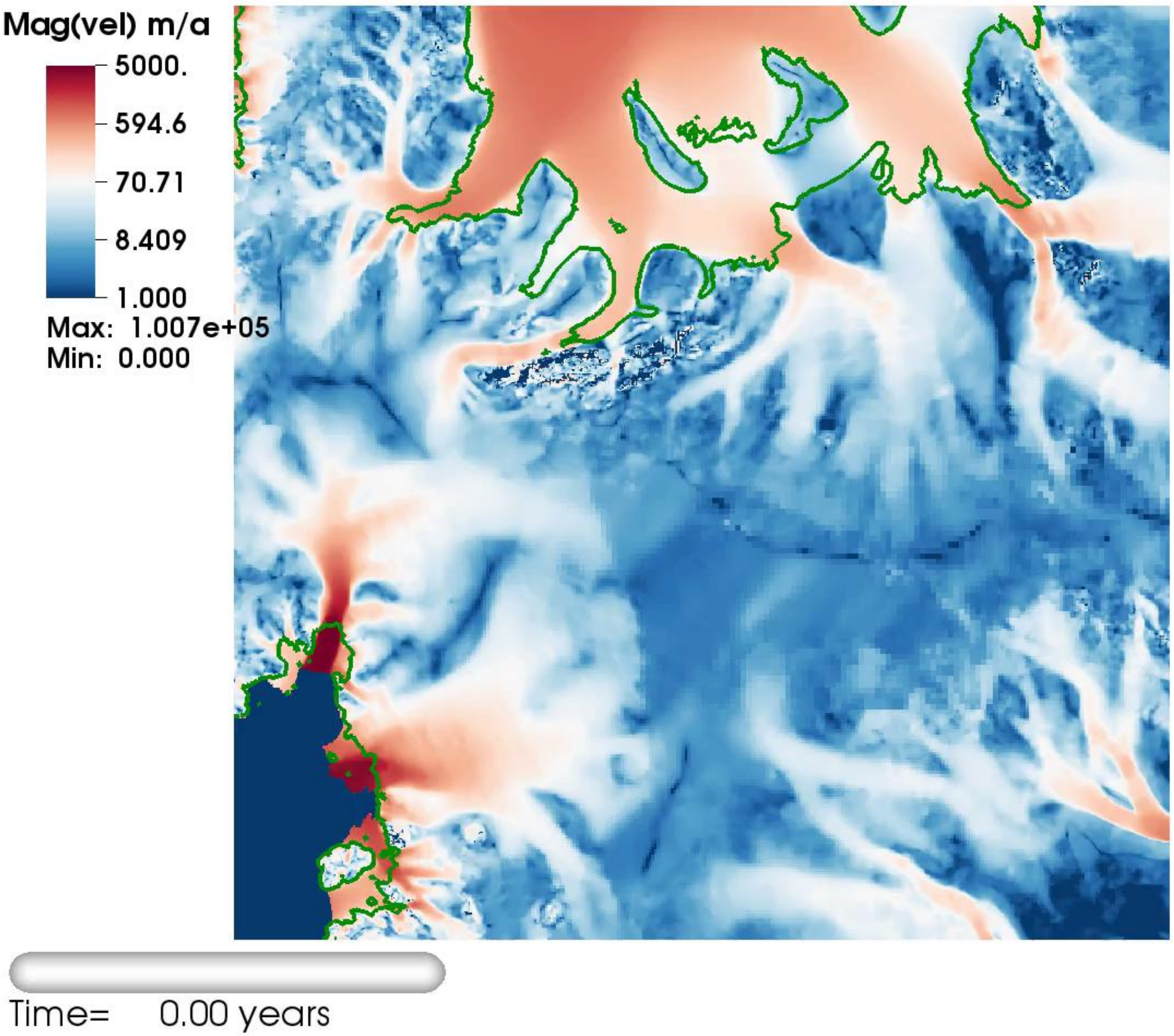
- **Lower plot** -- Rate of Change
  - Big spike – WAIS collapse
  - Timing is a function of resolution



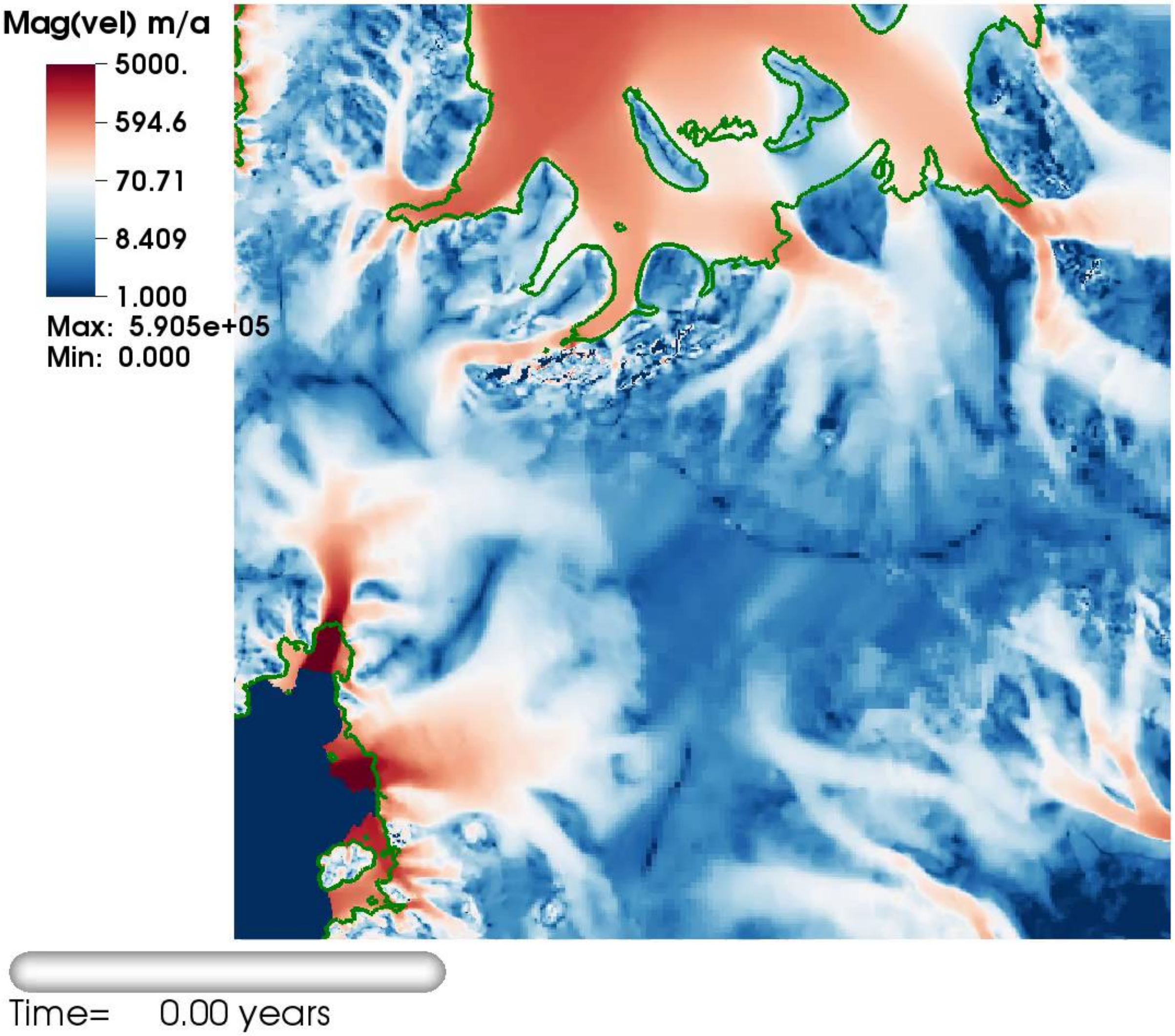
Thwaites-Rutford - 500m Resolution



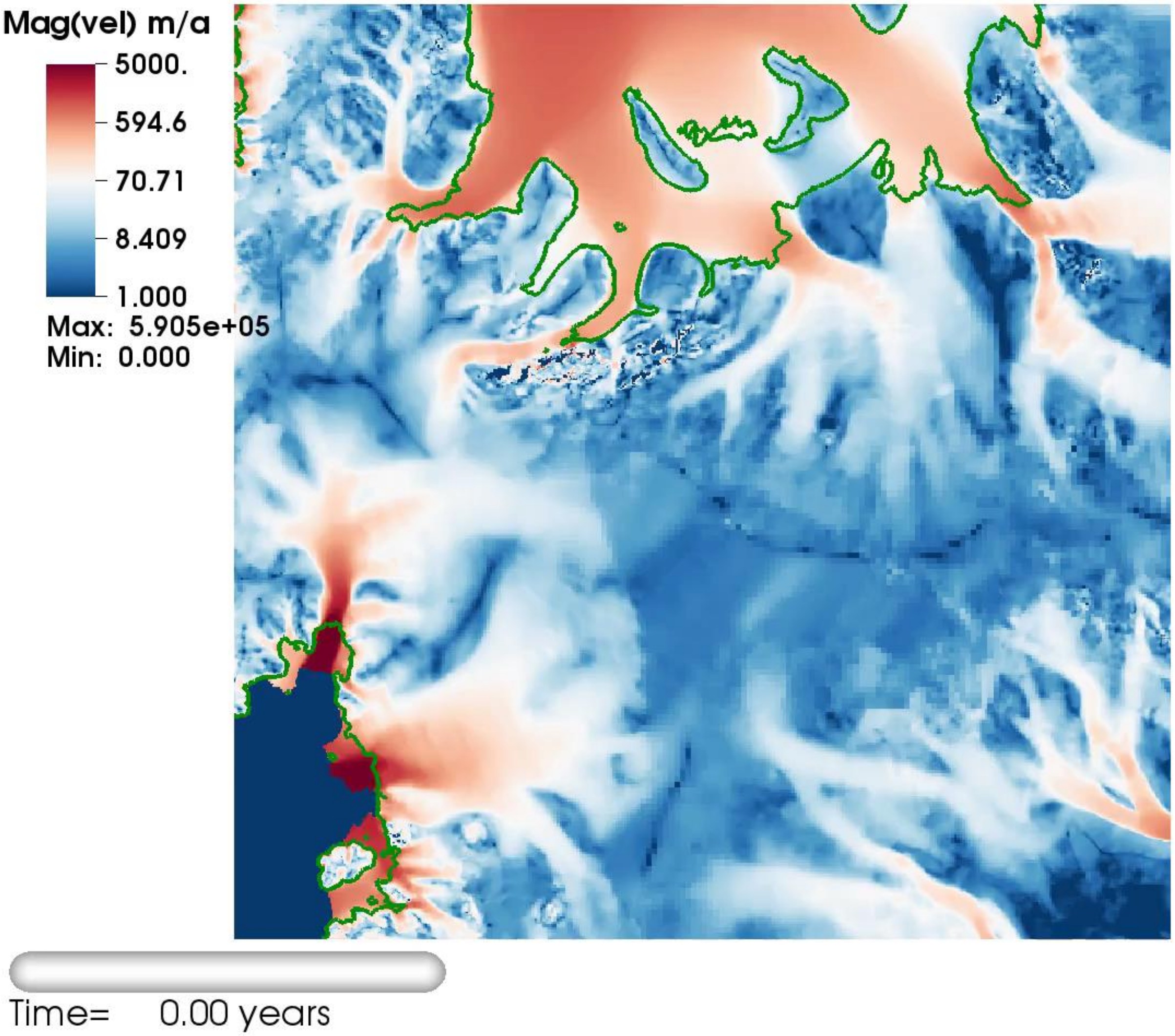
Thwaites-Rutford - 1km Resolution with GLI



Thwaites-Rutford, 2km, with GLI



Thwaites/Rutford, 2 km, with GLI



Results, cont

- Complete WAIS collapse in sufficiently-resolved runs.
- Lower-resolutions produce lower GL mobility, lower SLR contributions.
  - Thwaites: no or delayed retreat for coarser resolutions (4 km)
- Qualitative difference between under-resolved and sufficiently resolved (in the asymptotic regime)
- Subgrid scheme is worth about a factor of 2 in mesh spacing.
- Max change in VoF is approx. 4 m S.L.E.

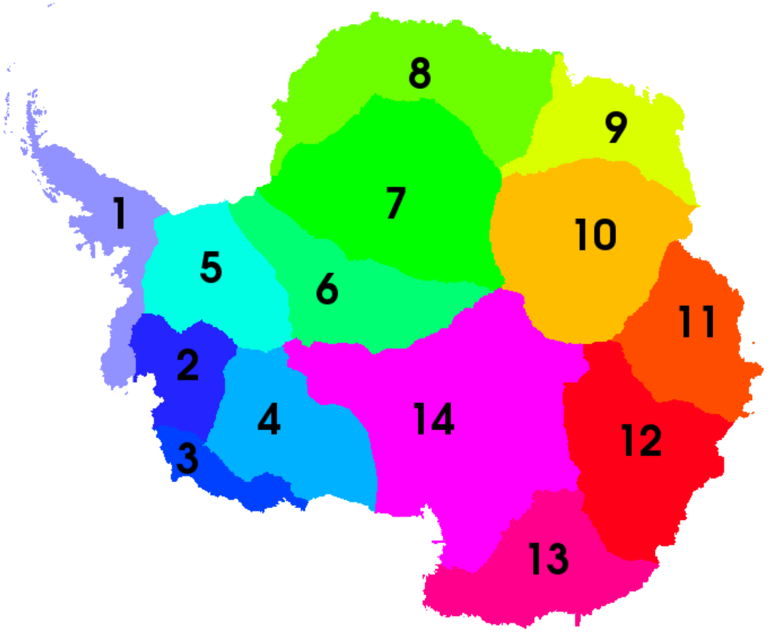
Conclusions: resolution requirements

- For this exercise, subgrid GL interpolation scheme is worth roughly a factor of 2 in resolution (one level of AMR refinement for us)
- **1 km or better resolution** needed to get dynamics right
- Under-resolution can produce ***qualitatively*** wrong response
- Fine resolution needed at the GL at all times.

Antarctic vulnerability to warm-water forcing

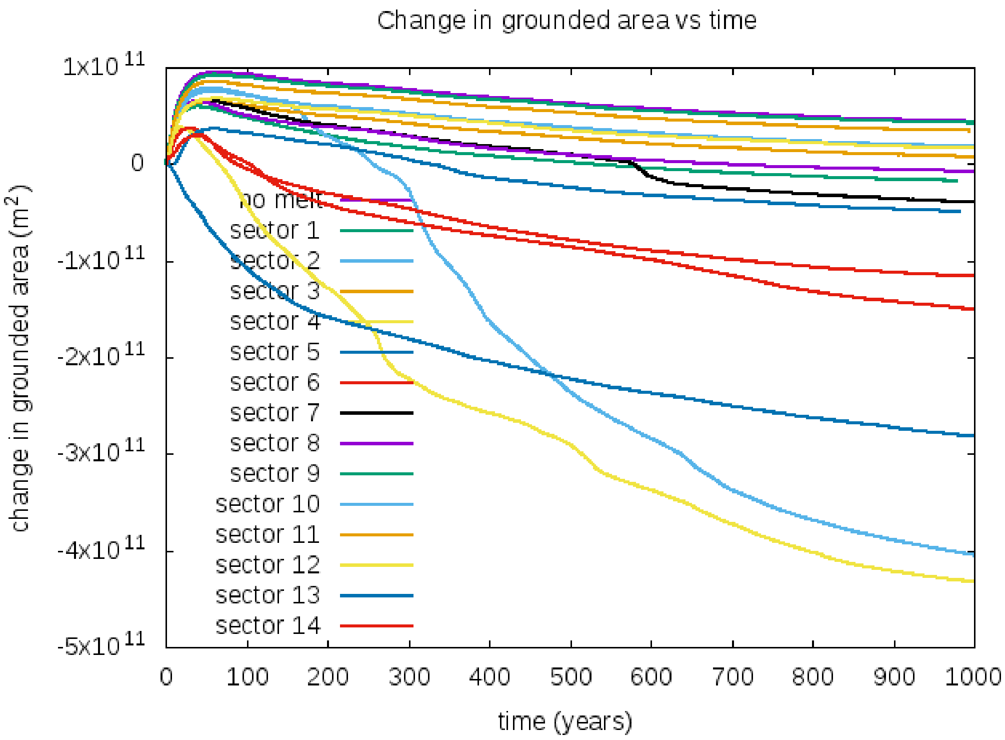
- Basic idea - try to understand where AIS is vulnerable to forcing from warm-water incursions

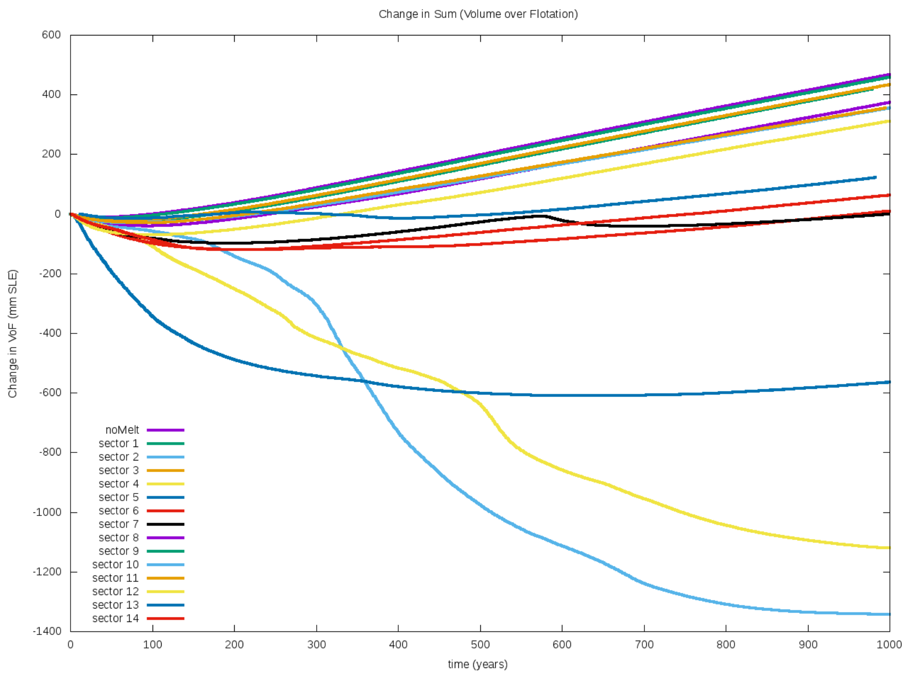
Antarctic sectors



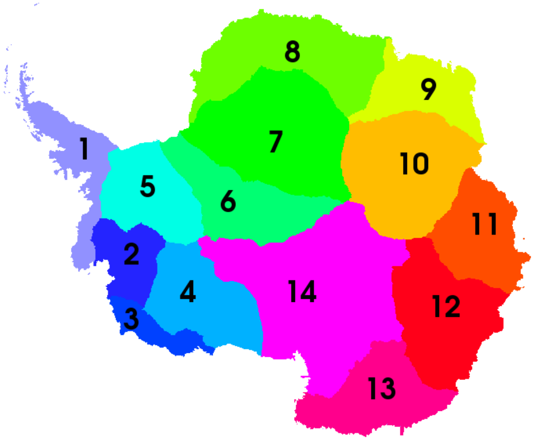
- Divide AIS into sectors
- For each sector in turn (and for some combinations), apply extreme melt forcing
- Run for 1000 years.
- Use 1 km finest resolution with GL subgrid friction

Results



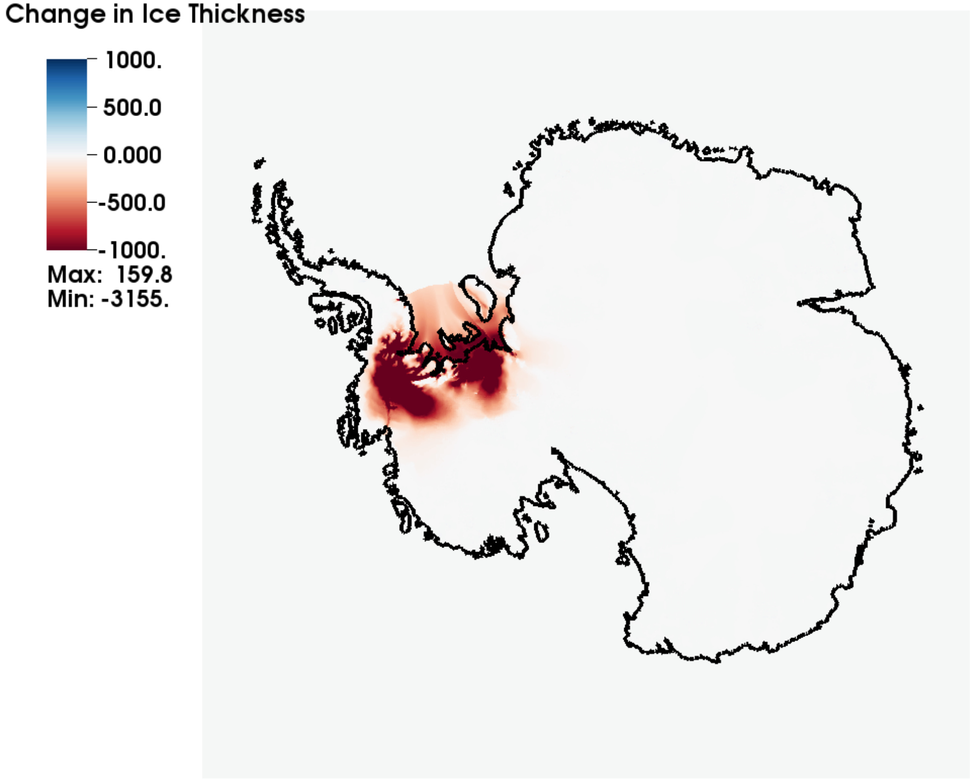


- WAIS-connected sectors (2,4,5) – largest response
- Intermediate response from 6,7,13,14
- Sector 11 – issues with Bedmap2

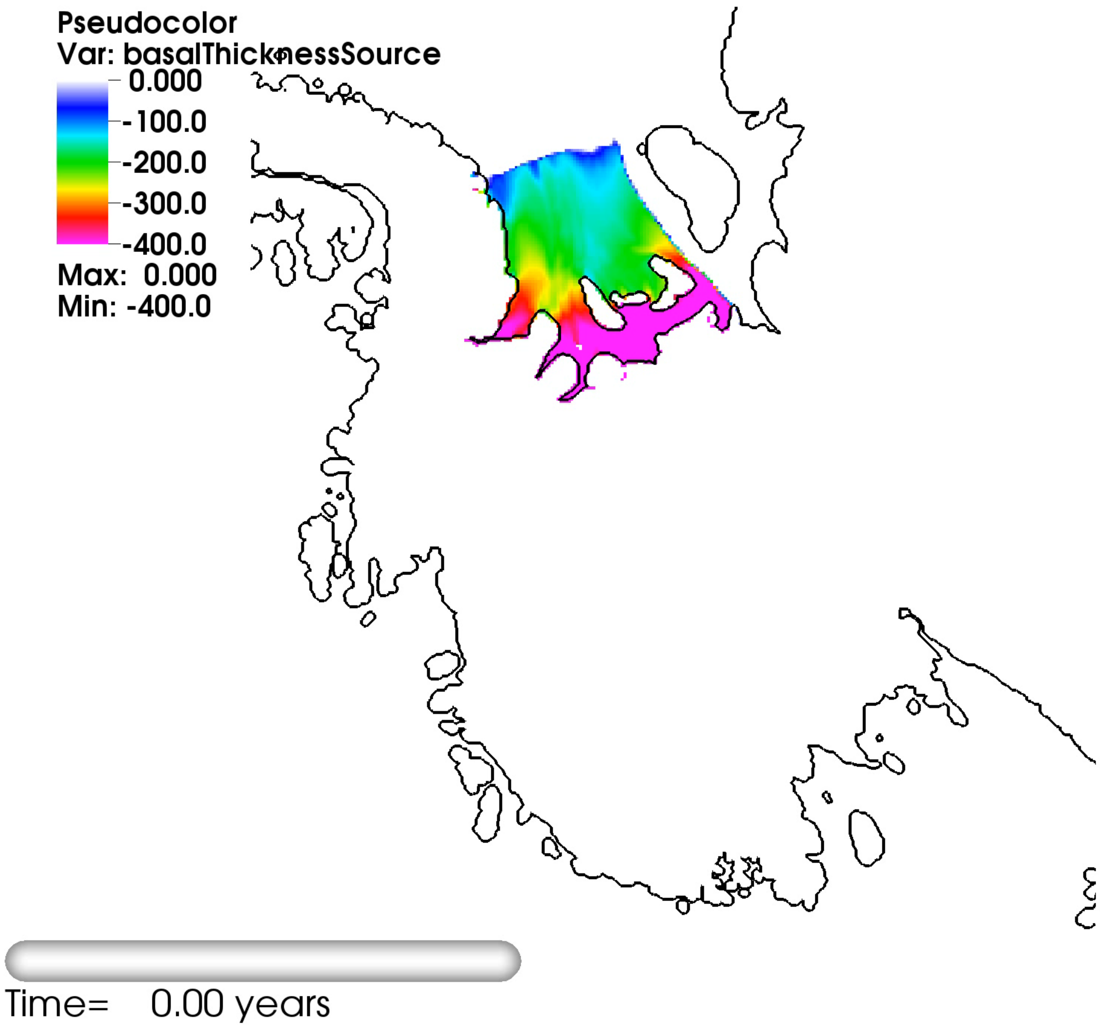


Sector 5 (Western Ronne)

- GL retreat moves out of sector…
- Substantial retreat into WAIS even after direct forcing ends
- 1.03 m SLE

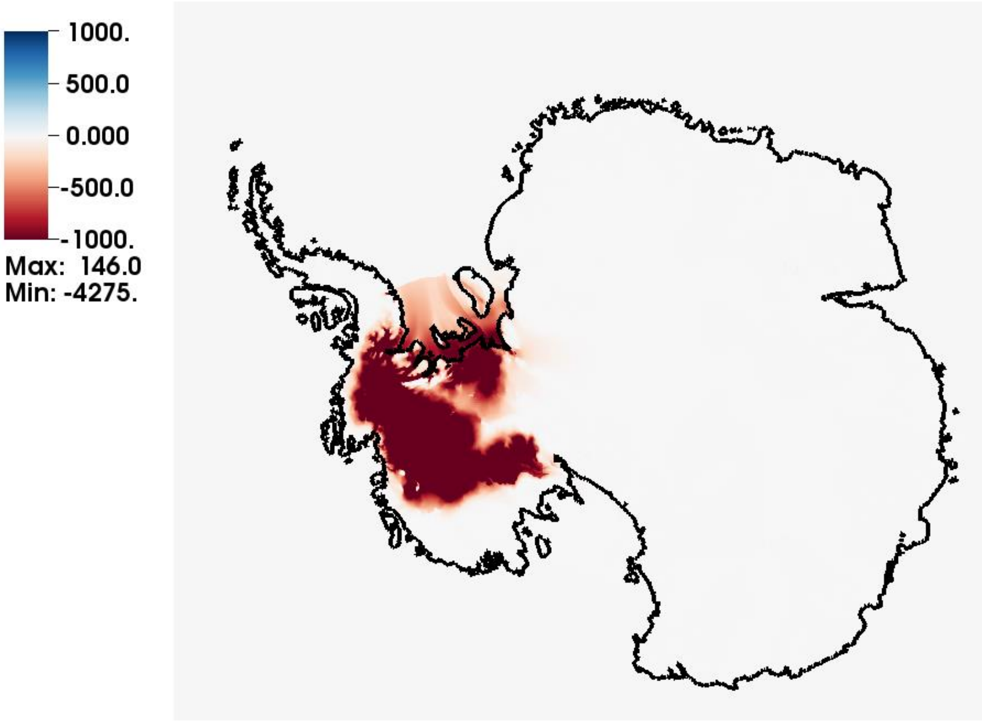


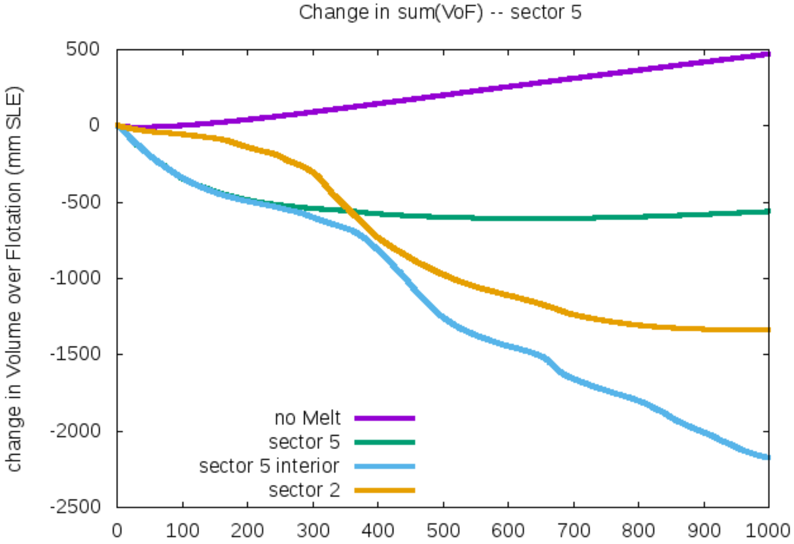
Sector 5, cont

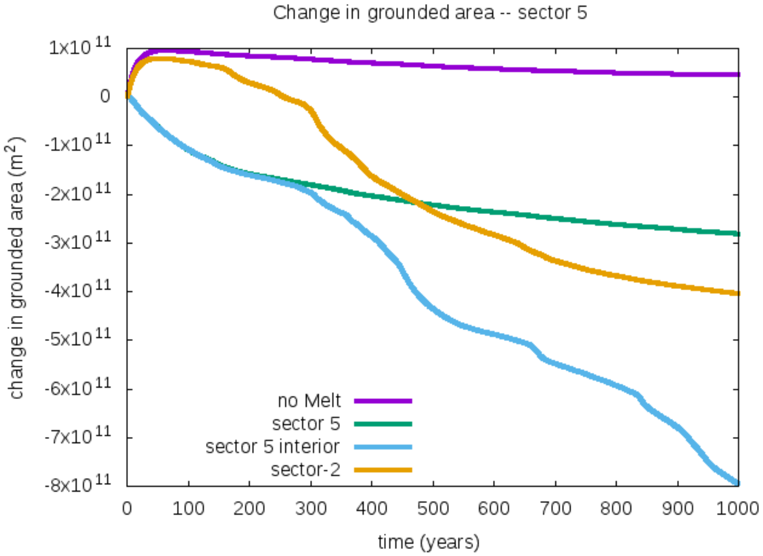


Sector 5 -- Enhanced melting..

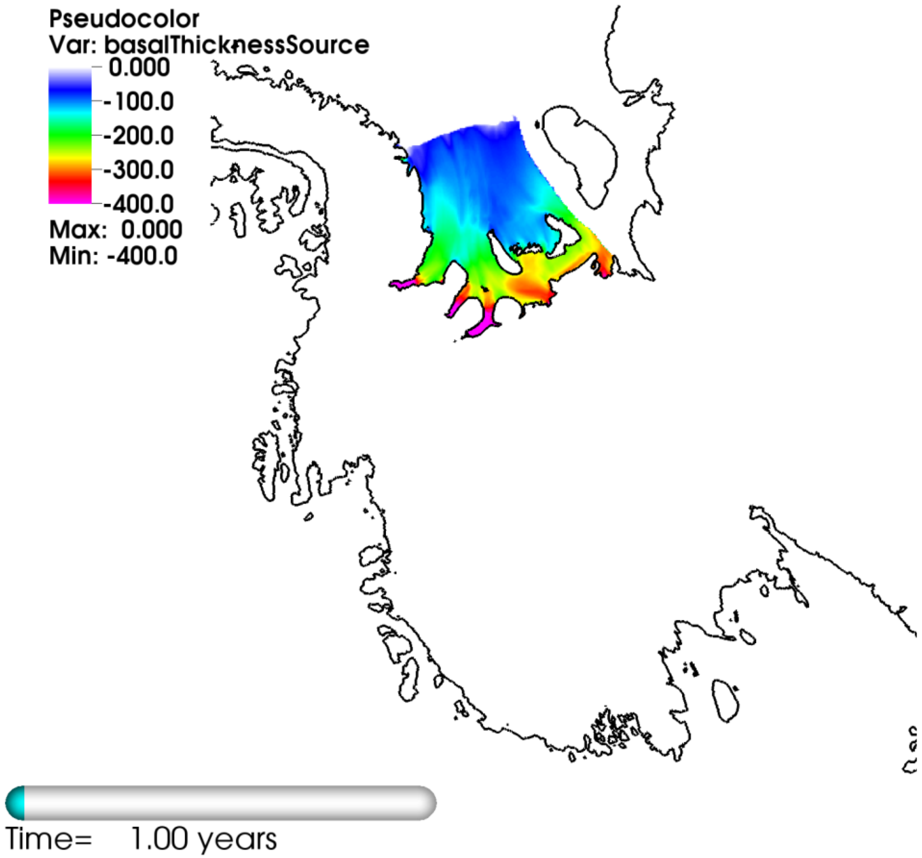
- Allow melt to follow GL into interior



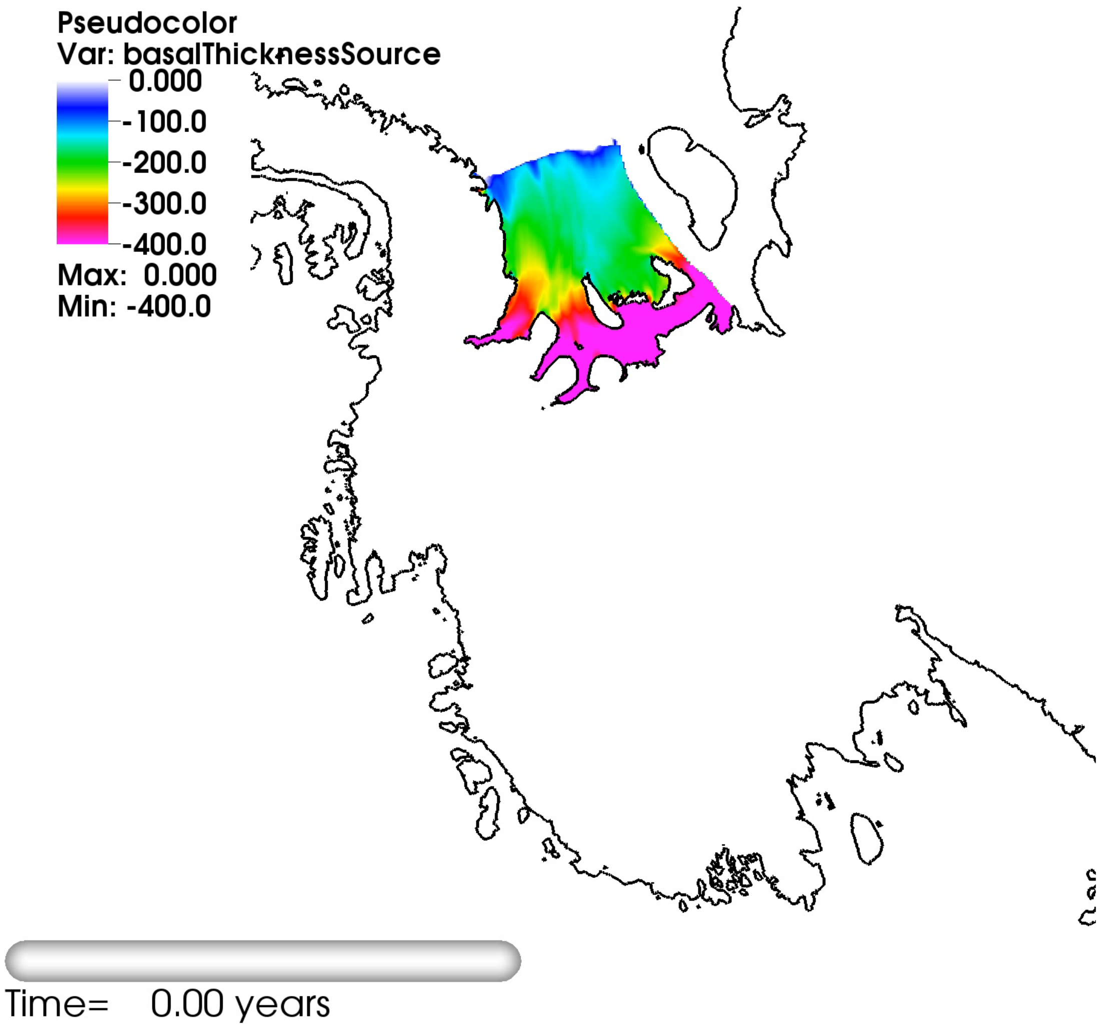




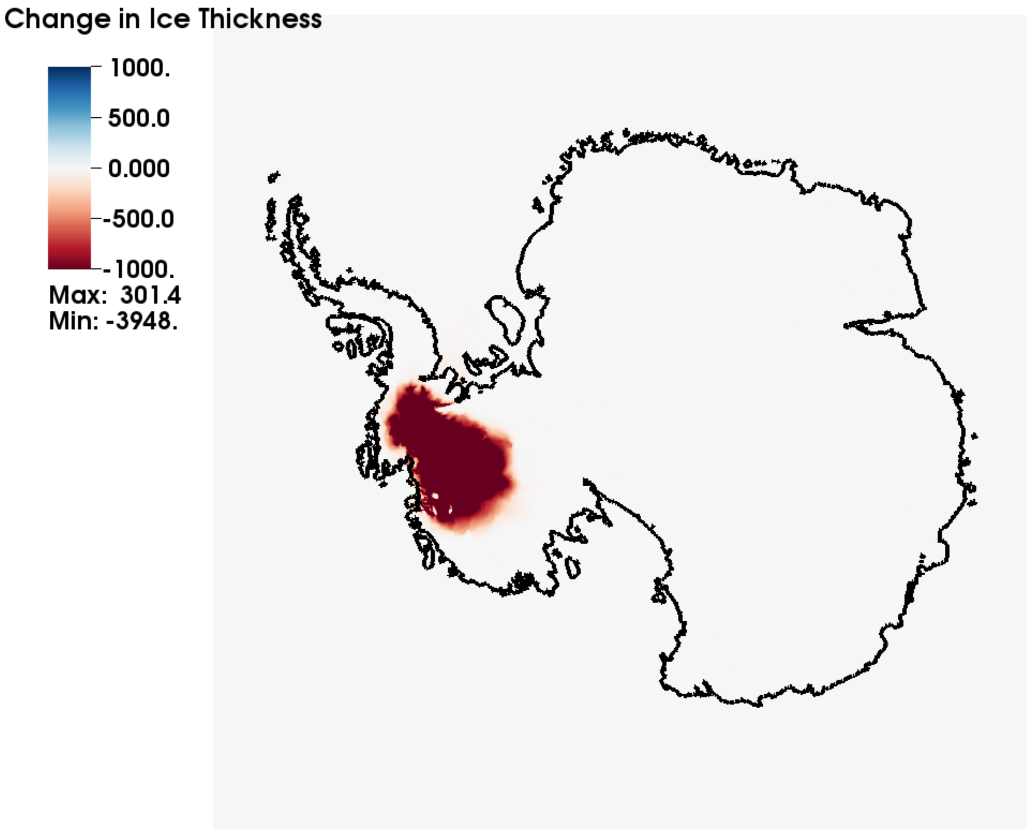
- Increase to 2.64 m SLE (from 1.03 m SLE)

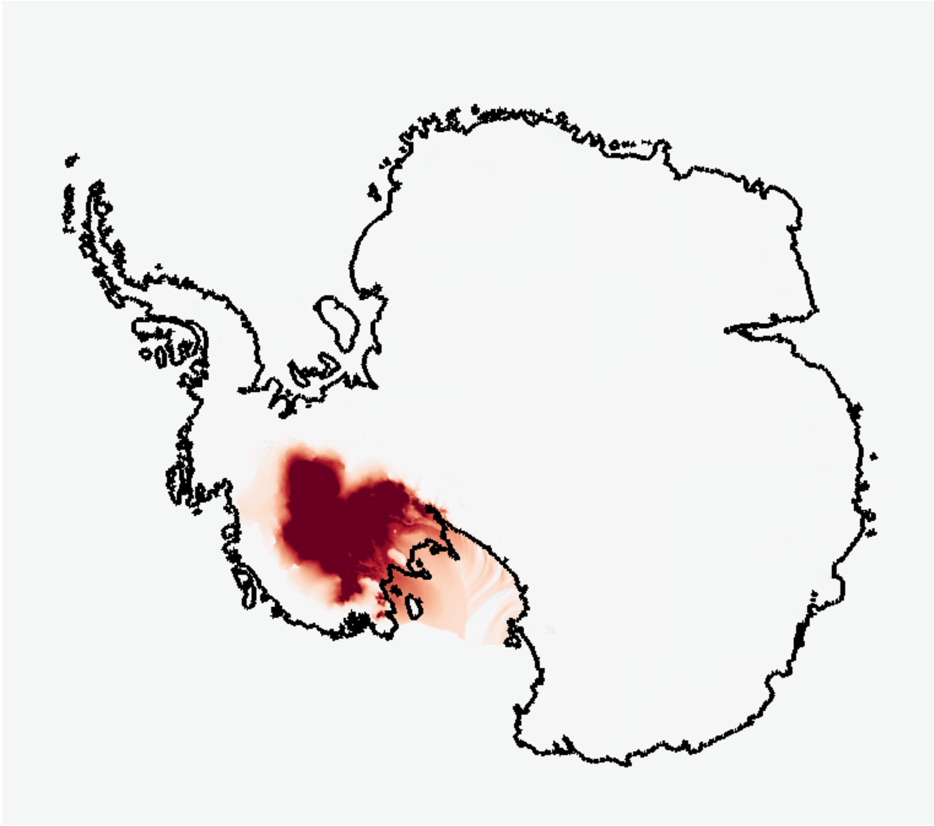

Pseudocolor
Var: basalThicknessSource
0.000
-100.0
-200.0
-300.0
-400.0
Max: 0.000
Min: -400.0
Time= 1.00 years

Sector 5, interior melting



Sectors 2 & 4

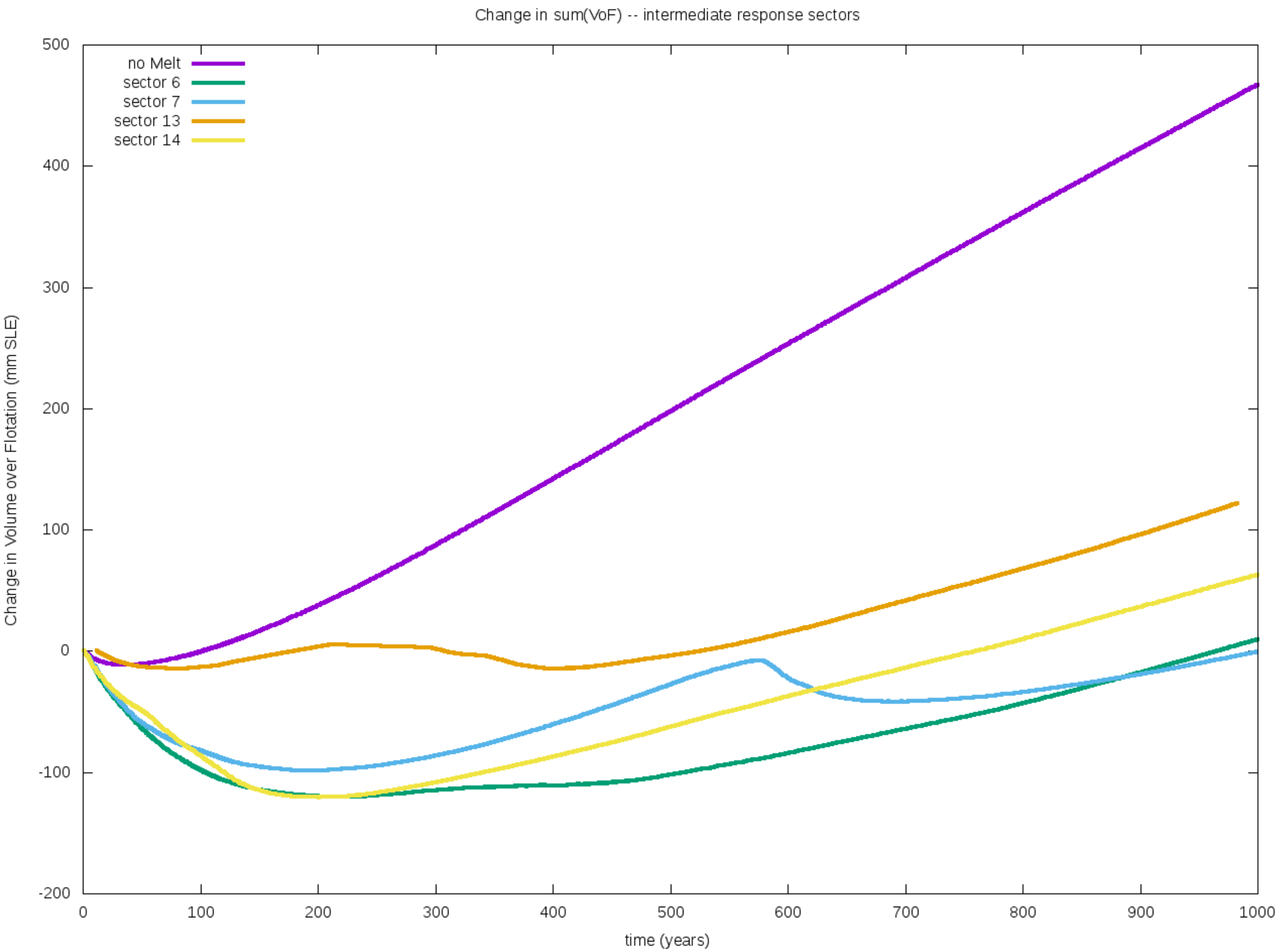




Sector 2 (ASE): 1.8m SLE

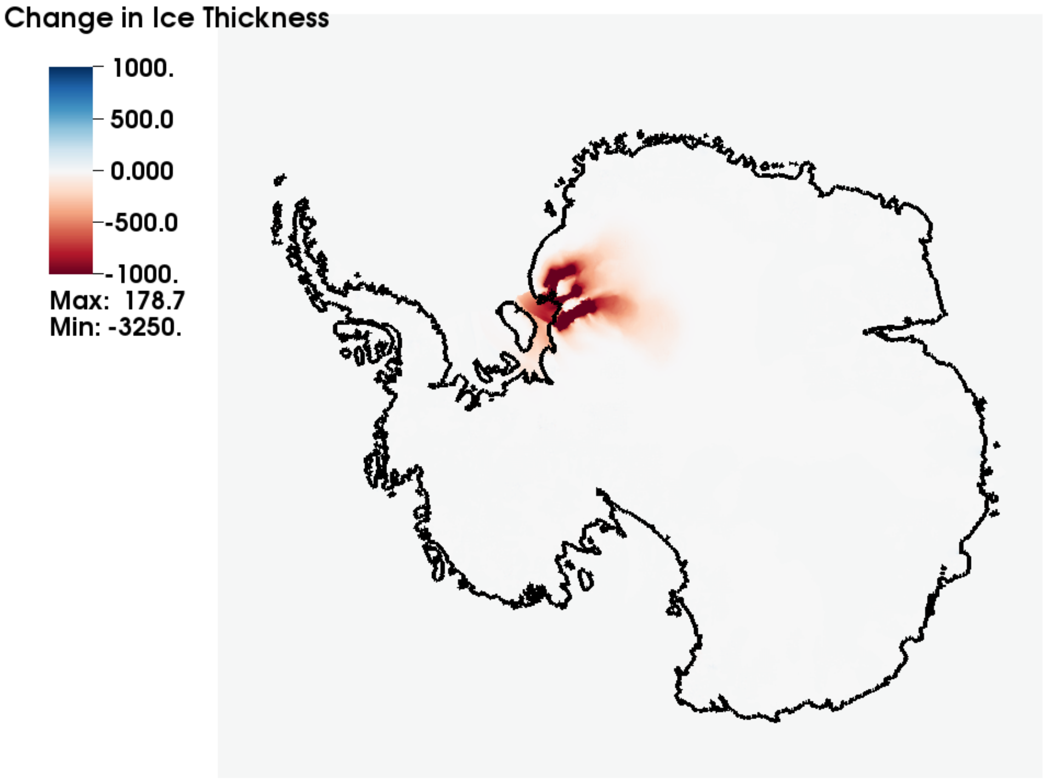
Sector 4 (Ross): 1.59m SLE

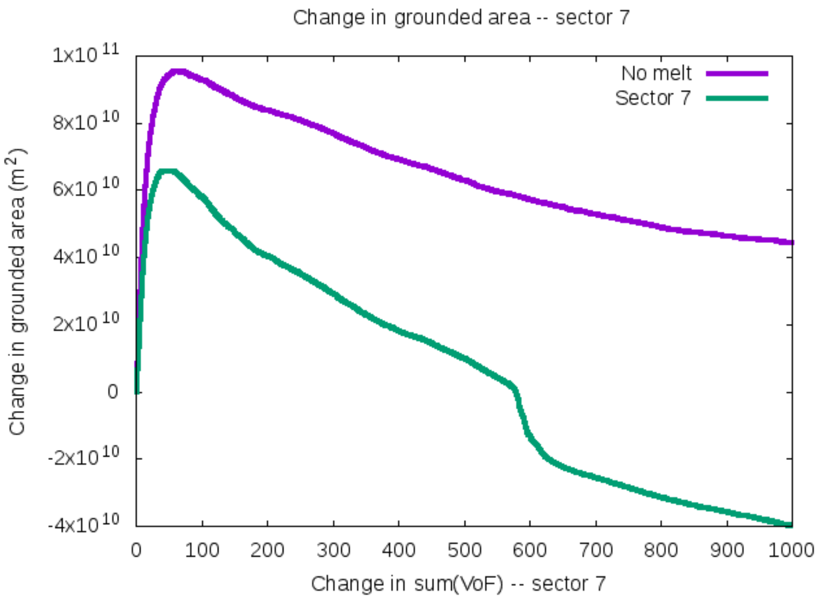
Intermediate loss sectors

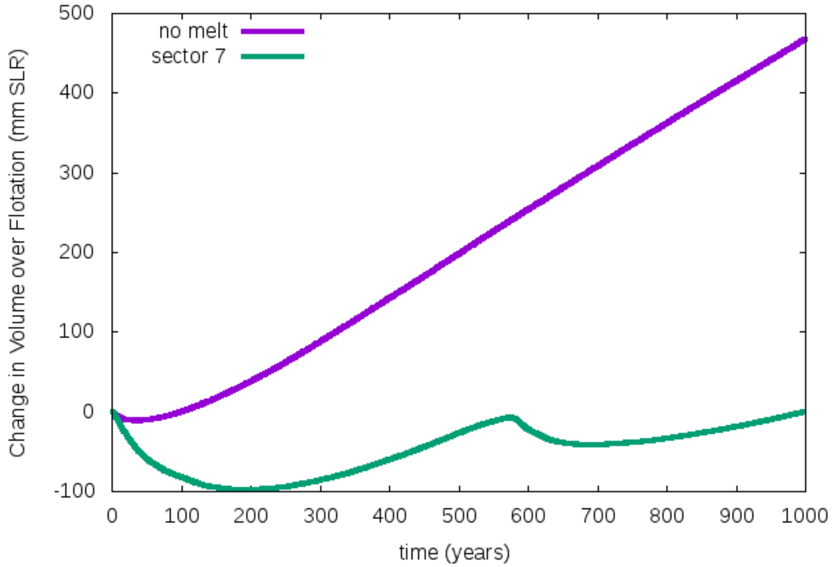


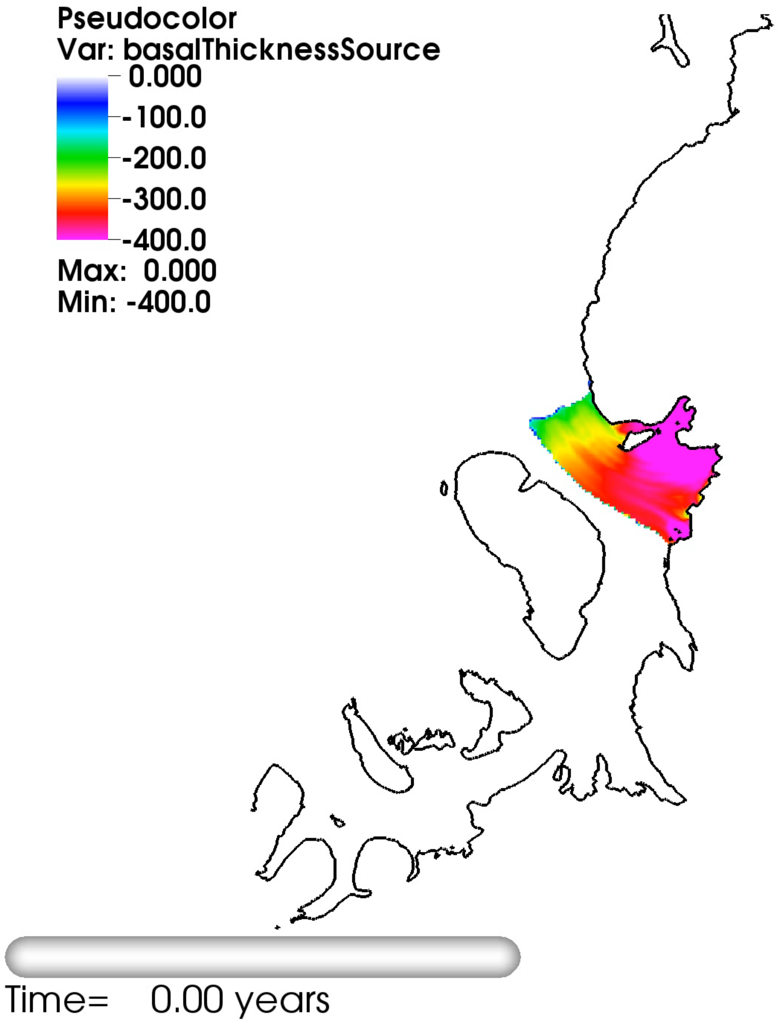
Intermediate loss sectors - Sector 7

- Sector 7 (Recovery Ice Stream)
  - 0.467 m SLE









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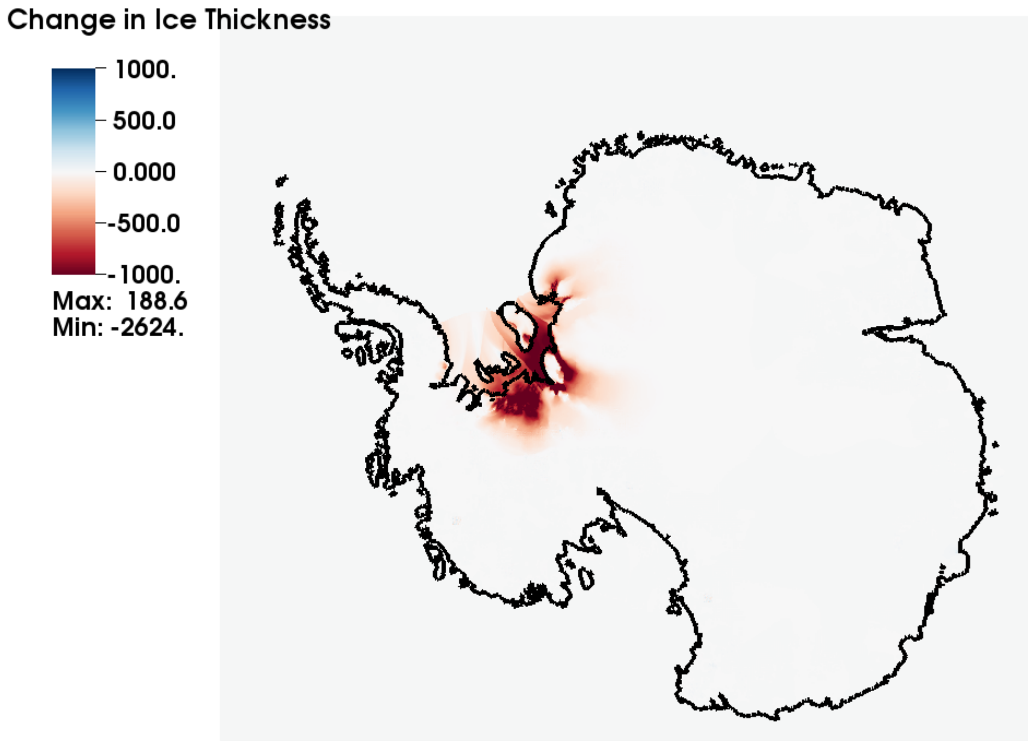
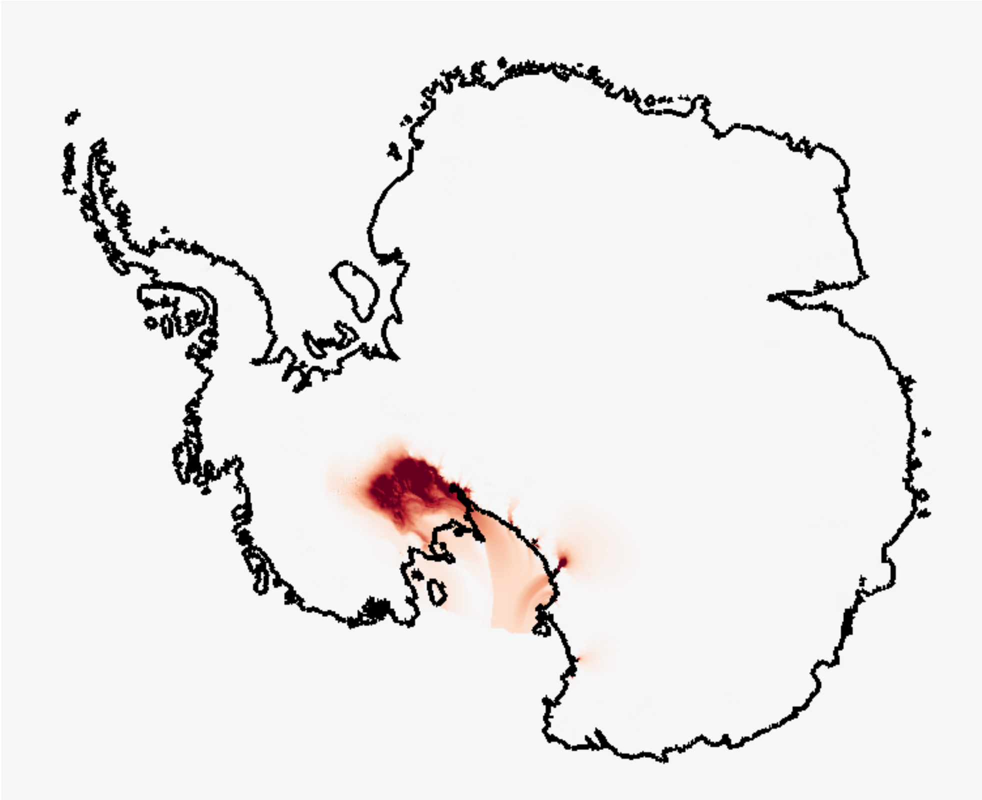
Sectors 6 & 14

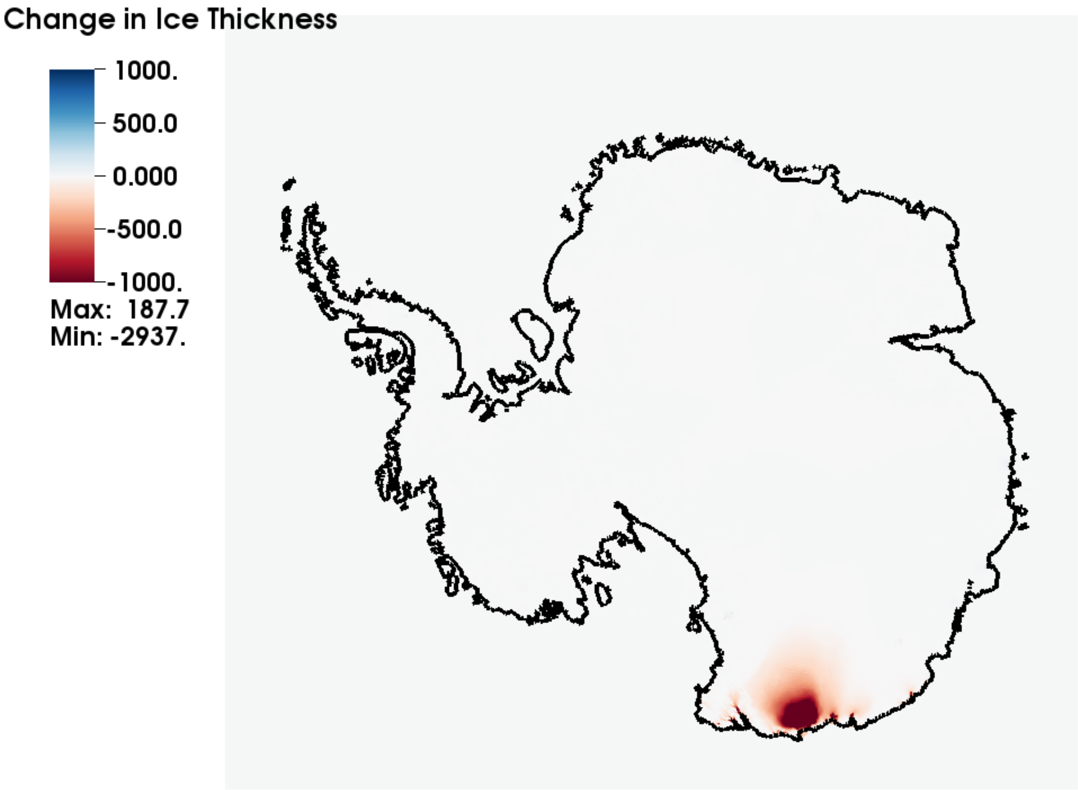




Sector 6: 0.457 m SLE

Sector 14: 0.404 m SLE

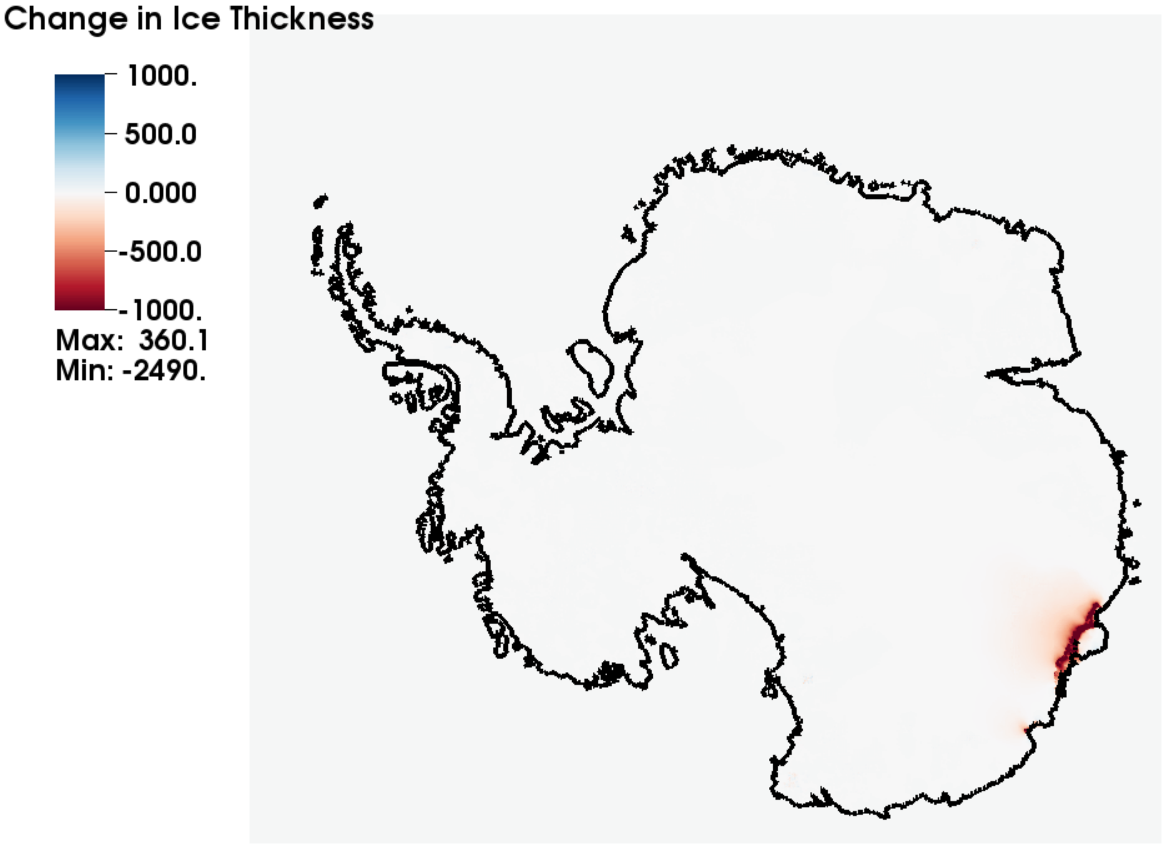
Sector 13



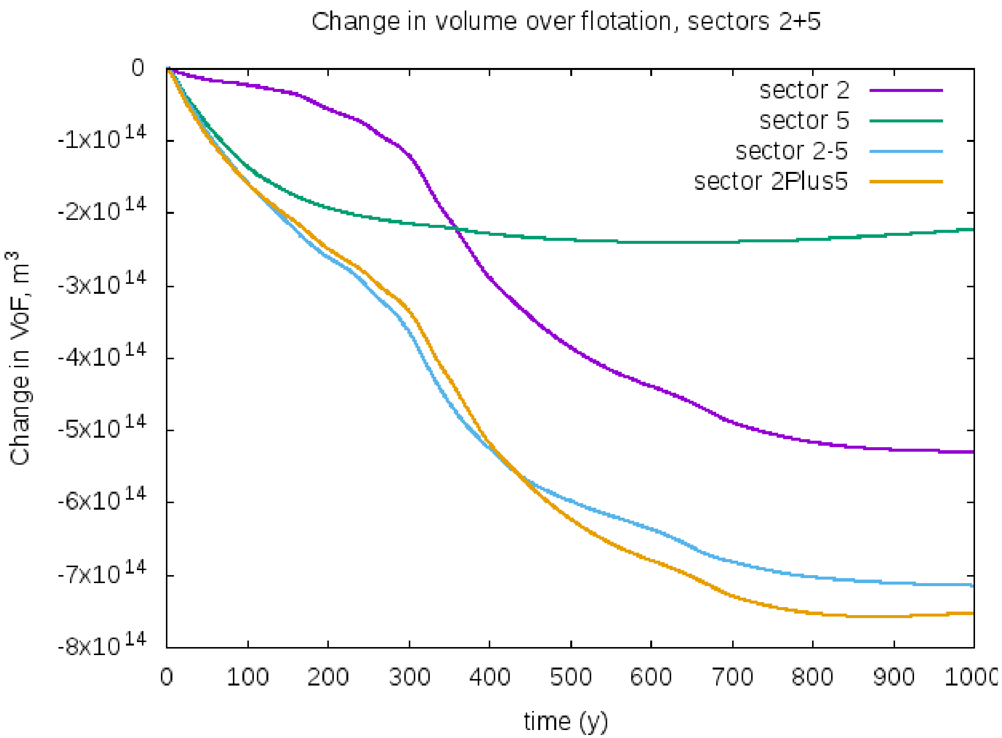
Sector 13: 0.345 m SLE

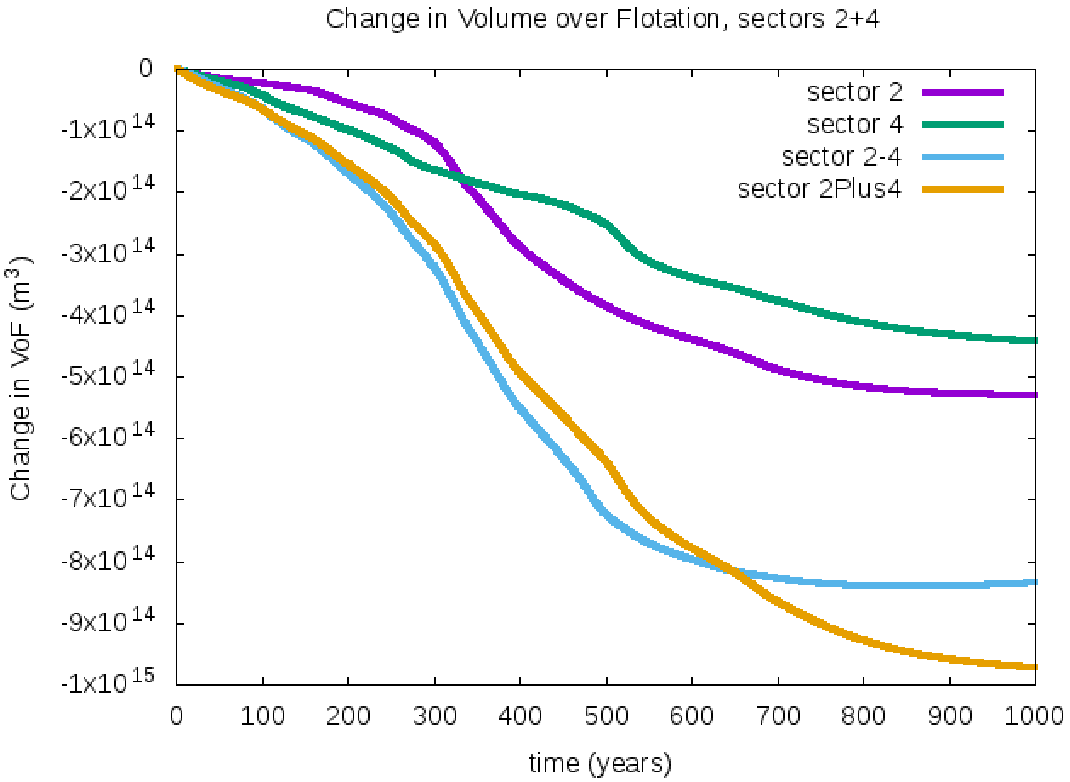
What about Totten?

- With Bedmap2 topography, limited vulnerability..
- Sector 12 – 0.156m SLE



Combinations: 2 (ASE) &4 (Ross), 2&5 (Ronne))





- Green, purple – single sectors
- Blue – combination of the two
- Yellow – sum of the two single-sector runs
- For WAIS sectors, roughly independent at start, after O(200a), start to interact

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Conclusions (and caveats)

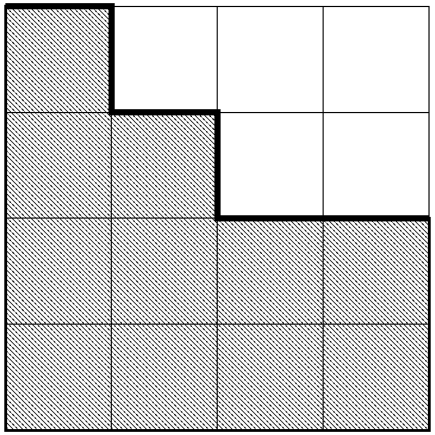
- Primary vulnerability still WAIS.
- Limited potential from EAS
- WAIS vulnerable from any of three sectors
  - (2 of which are large cold ice shelves)
- Intermediate vulnerability in Ronne, Western Ross sectors
- Everything dependent on Bedmap2 geometries…

Thank you!

Extras

Subgrid-scale friction interpolation

- **<u>BISICLES standard GL scheme:</u>**
  - Grounding line located at cell faces
  - Individual cells either grounded or floating
  - Basal friction is located at cell centers
  - Use one-sided differences to compute quantities like driving stress
  - (better approximation based on cut-cells is in development)



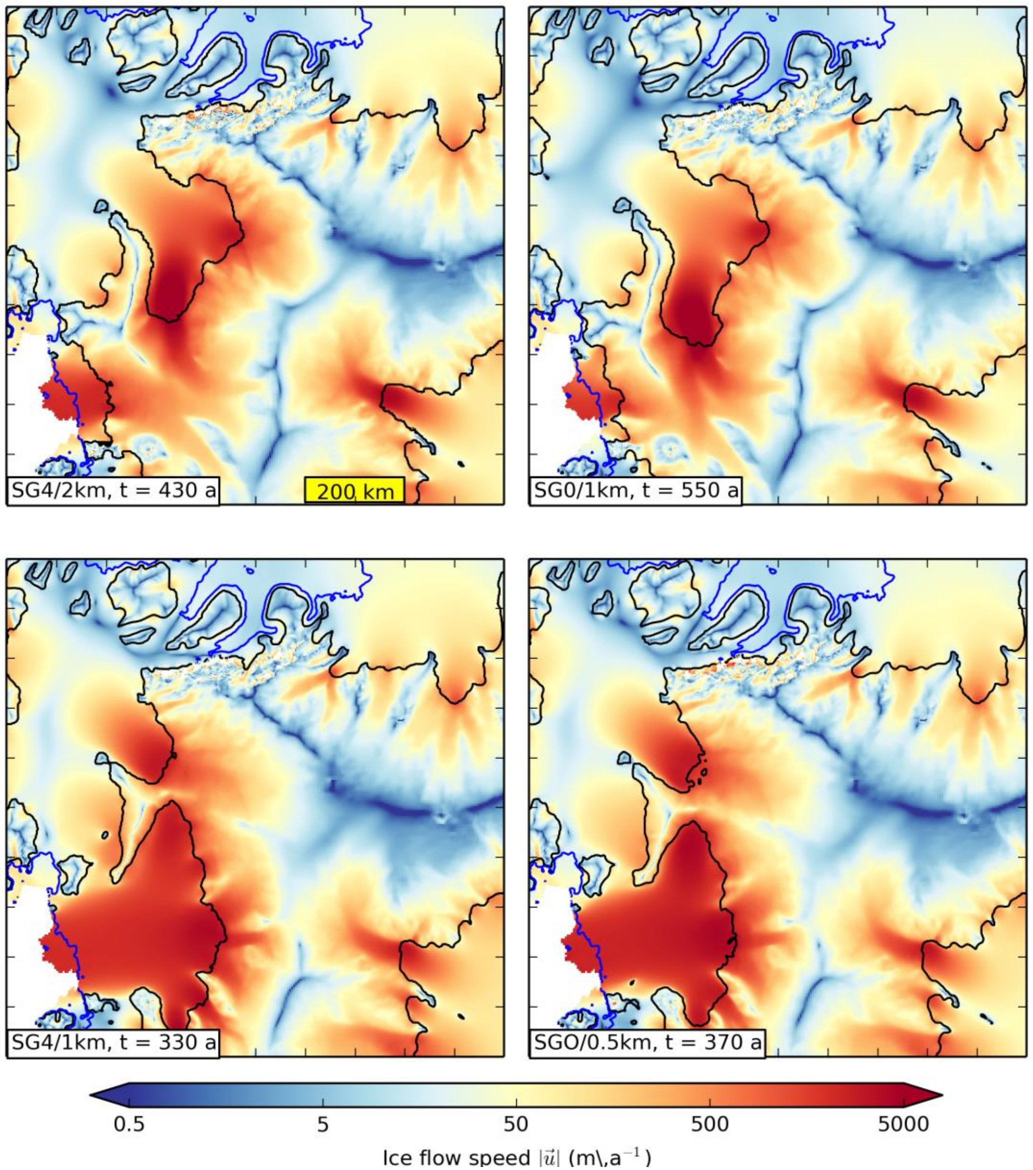
Subgrid-scale friction interpolation

❑ Alternative sub-grid Scheme:

- Based on Feldmann et al (2014)
- Divide cells into quadrants.
- Bilinearly interpolate thickness over flotation $(h - h_f)$ in each quadrant based on neighboring cell centers.
- Subdivide each quadrant into $2^n \times 2^n$ sections and evaluate interpolated thickness over flotation in each segment to compute weighted grounded area.
- Then can scale basal friction by the grounded fraction in each cell.

- In this work, use $n = 4$.

Thwaites-Rutford - effect of resolution

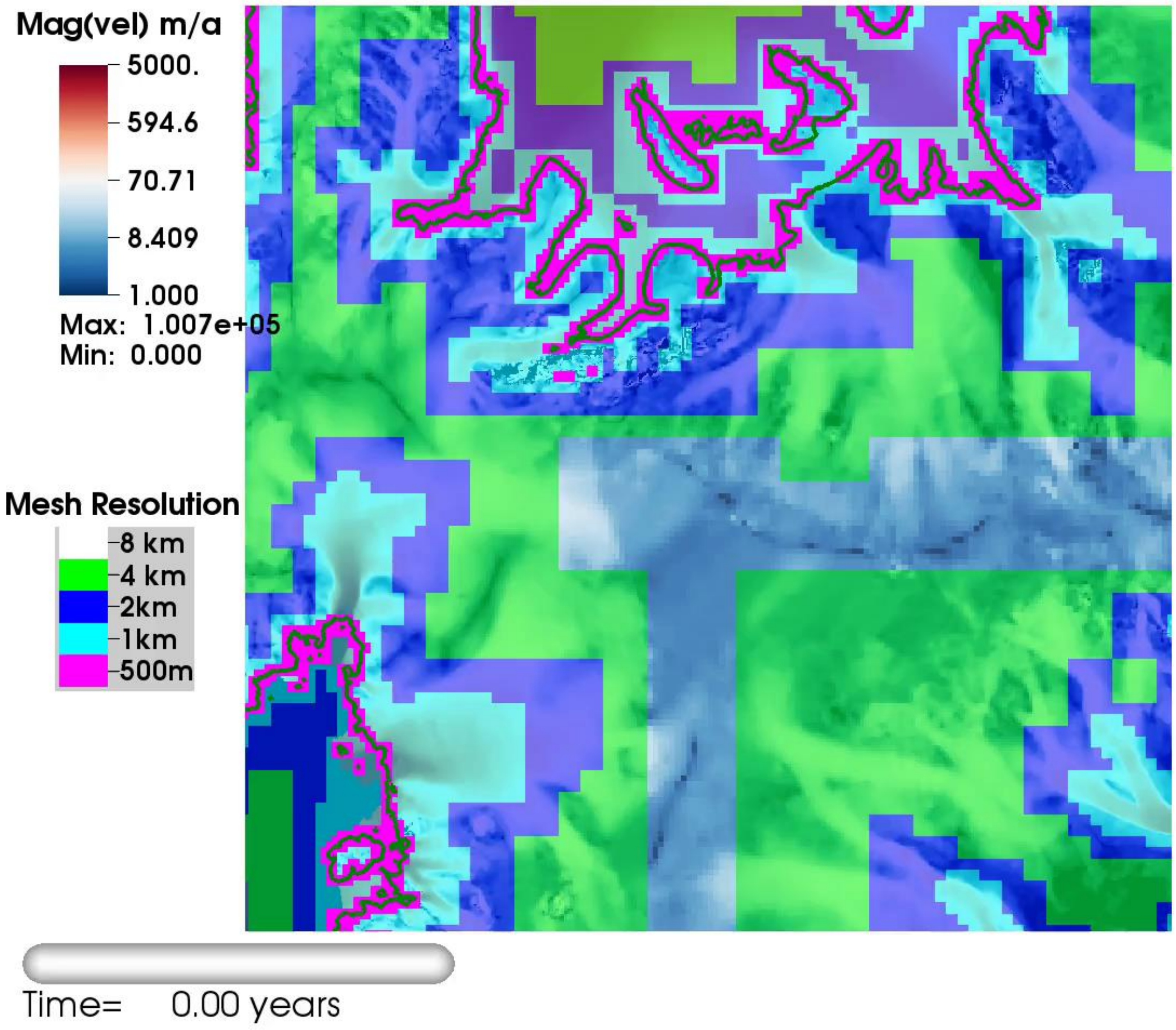


Overall Conclusion

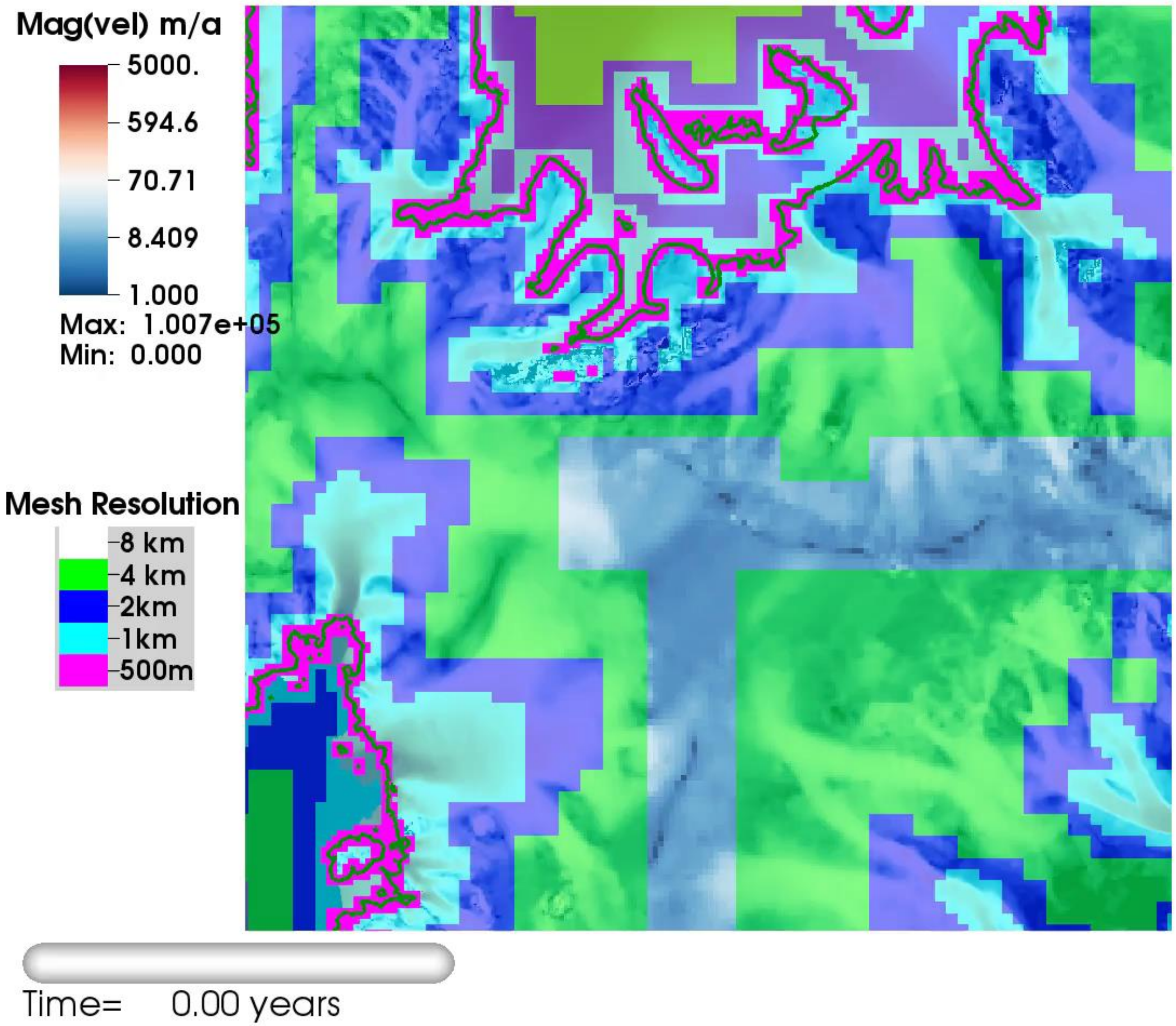
It's up to us as modelers to demonstrate that our models are sufficiently resolved!

(hopefully preaching to the choir here…)

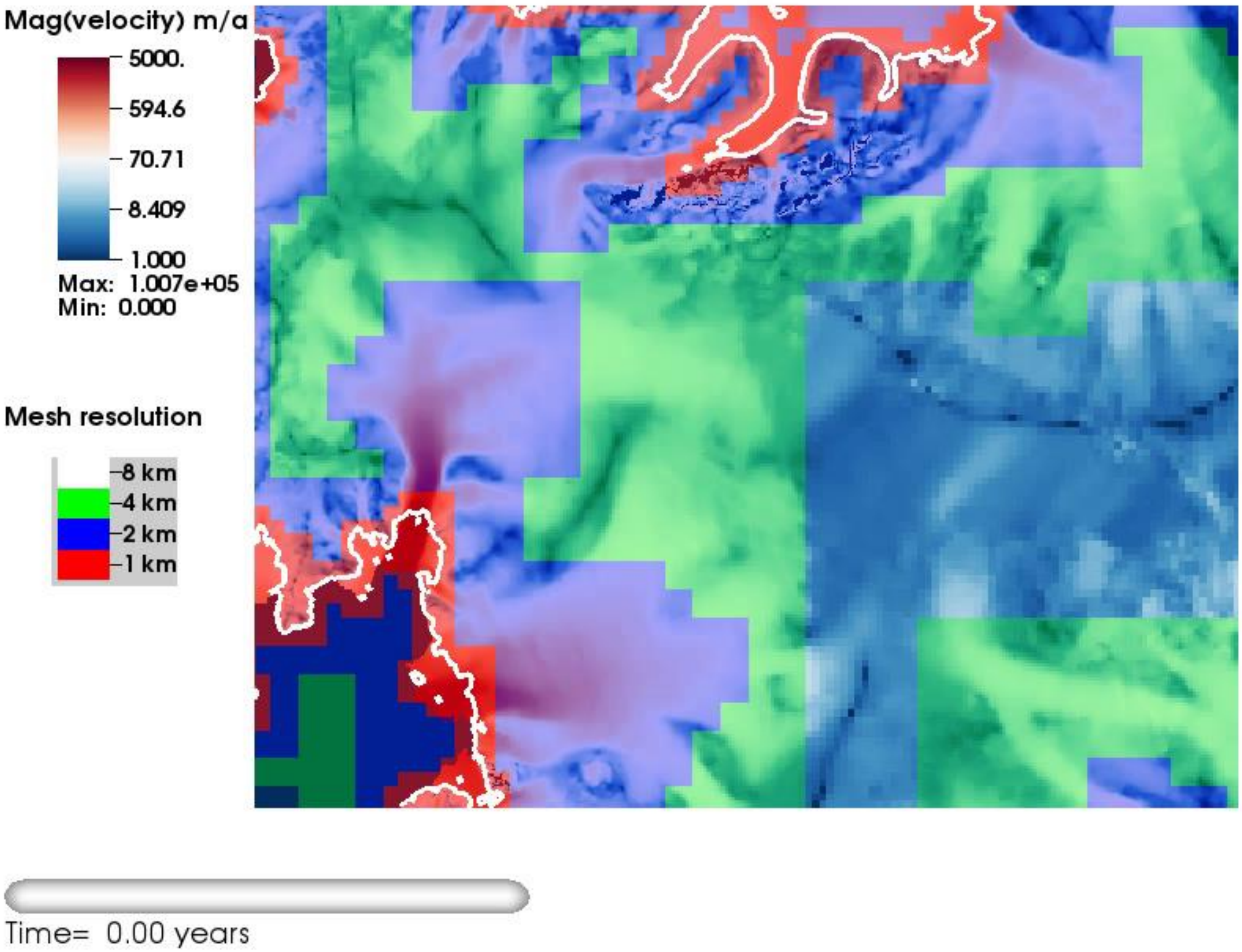
Mesh evolution (500m mesh)



Mesh evolution (500m finest mesh)



No-regridding



No-regridding